

# Optimal Feed-back Switching Control for the UPFC Based Damping Controllers

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**Abstract**—This paper presents an optimal feed-back switching concept for the Unified Power Flow Controller (UPFC) based damping controllers for damping low frequency oscillations in a power system. Detailed investigations have been carried out considering switching between two optimal damping controllers; one with respect to modulating index of shunt inverter  $m_E$  and another with respect to modulating index of series inverter  $m_B$ . The proposed UPFC switching model presented here is tested on the modified SMIB linearised Phillips-Heffron model of a power system installed with UPFC using MATLAB/SIMULINK® platform. The investigations reveal that the proposed optimal feed-back switching control between UPFC damping controllers  $m_E$  and  $m_B$  provides moderately better performance with respect to settling time for both individual controllers as well as coordinated damping controller.

**Index Terms**— OFSC, COC, UPFC, LQR, SMIB, Phillips-Heffron Model.

## I. INTRODUCTION

The Unified Power Flow Controller (UPFC) is a multi-functional flexible AC Transmission (FACTS) device, whose primary duty is power flow control. The secondary functions of the UPFC can be voltage control, transient stability improvement, oscillations damping. It combines features of both Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC).

Design of control strategies using FACTS devices such as UPFC for optimal power flow with improved performance is a major research concern of power system control community. Wang [1] has presented a modified linearised Phillips-Heffron model of a power system installed with UPFC and addressed basic issues pertaining to design of UPFC based power oscillation damping controller along with selection of input parameters of UPFC to be modulated in order to achieve desired damping. Wang has not presented a systematic approach for designing the damping controllers. Further, no effort seems to have been made to identify the most suitable UPFC control inputs, in order to arrive at a robust damping controller for optimal performance of all the state variables. However, in recent times, researchers are working on the selection of UPFC control parameter for the design of UPFC damping controller by applying different control techniques like Phase Compensation, Fuzzy Logic, optimal control techniques like Linear Quadratic Regulator

(LQR), H-infinity, particle swarm optimization etc [2-6]. Some of the examples are described here. In [2] authors have shown the control inputs  $\delta_E$  and  $\delta_B$  to provide robust performance when compared to the other damping controllers by applying a phase compensation control technique with respect to state space variable speed. In [3] authors have presented iterative particle swarm optimization (IPSO) based UPFC controller to achieve improved robust performance and to provide superior damping in comparison with the conventional particle swarm optimization (CPSO) for the control inputs  $\delta_E$  and  $m_B$ . In [4] author has presented multi machine system, where some of the states having larger settling time with conventional LQR are well regulated with multistage LQR.

In the current paper, for the modified SMIB linearised Phillips-Heffron model, after doing a preliminary control analysis with individual inputs and coordinated inputs, a switching strategy between individual controllers is suggested for UPFC devices such that the steady state response and settling time will be moderately better for all the four state space variables simultaneously for either cases of individual inputs as well as coordinated inputs.

Paper is organized as follows, in Section II, modified SMIB linearised Phillips-Heffron model is described. It is followed by some preliminary analysis, first with individual controllers later with coordinated controller in Section III. Section IV describes the switching model for Phillips-Heffron plant with UPFC controllers along with the proposed switching rule. Results and analysis follow in the concluding section.

## II. DYNAMIC MODEL OF POWER SYSTEM WITH UPFC

H.F. Wang has presented the following state space model for the modified SMIB linearised Phillips-Heffron power system [1, 5].

$$\dot{x} = Ax(t) + Bu(t) \quad (1)$$

Where, the state variables are the rotor angle deviation ( $\Delta\delta$ ), speed deviation ( $\Delta\omega$ ), q-axis component deviation ( $\Delta E'_q$ ), field voltage deviation ( $\Delta E_{fd}$ ) and input variables are modulating index and phase angle of shunt inverter ( $m_E, \delta_E$ ) and modulating index and phase angle of series inverter ( $m_B, \delta_B$ ). A and B represent the state and control input matrices given by

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -K_1 & -D & -K_2 & 0 \\ M & M & M & 1 \\ -K_4 & 0 & -K_3 & -1 \\ T'_{do} & 0 & T'_{do} & T'_{do} \\ -K_A K_5 & 0 & -K_A K_6 & -1 \\ T_A & 0 & T_A & T_A \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -k_{ps} & -k_{p\delta s} & -k_{pb} & -k_{p\delta b} \\ M & M & M & M \\ -k_{qs} & -k_{q\delta s} & -k_{qb} & -k_{q\delta b} \\ T'_{do} & T'_{do} & T'_{do} & T'_{do} \\ -k_A k_{vs} & -k_A k_{v\delta s} & -k_A k_{vb} & -k_A k_{v\delta b} \\ T_A & T_A & T_A & T_A \end{bmatrix}$$

All the relevant k-constants and variables along with their values used in the experiment are described in the appendix section at the end of paper.

### III. PRILIMINARY OPTIMAL CONTROL ANALYSIS

In this section, a preliminary analysis is done by controlling modulating index of shunt and series inverters  $m_E$  and  $m_B$  (the two chosen inputs for the current research) using LQR based controllers, in order to gain some insight into the system behavior and to arrive at a suitable switching strategy. Analysis is done in two stages. In the first stage the conventional optimal control (COC) analysis is done by selecting  $m_E$  or as the control inputs individually resulting in two separate Single Input Single Output (SISO) systems,

$$\dot{x} = Ax + \hat{B}u$$

Where  $\hat{B} = B_1$  the first column of the B matrix for the input  $m_E$ , and  $\hat{B} = B_3$  for the input  $m_B$ . The Control law is given by

$$u = r - Kx$$

Where,  $K = K_s$  and  $K = K_b$  are the controller gains for the inputs  $m_E$  and  $m_B$  respectively. Both  $K_s$  and  $K_b$  were designed by conventional LQR method and state variables were analysed. Refer Fig. 1 to 4. In the second stage COC analysis is done by selecting both and as the coordinated inputs resulting in a Multi Input Multi Output (MIMO) system with

$$B = [B_1 \quad B_3]$$

Now controller gain K is 2x4 matrixes for this MIMO model obtained by LQR algorithm for MIMO system. Analysis results for all the state variables are presented below in Fig. 1 to 4.

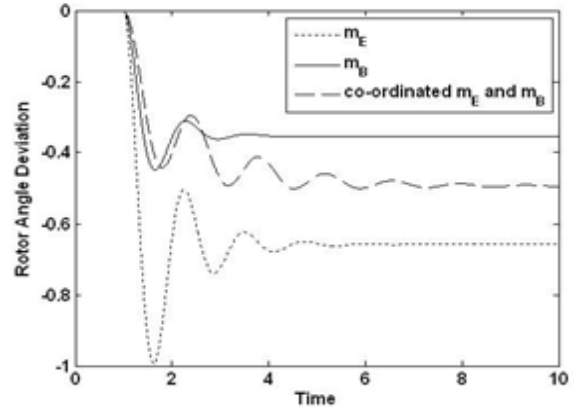


Figure 1: COC for Rotor Angle Deviation

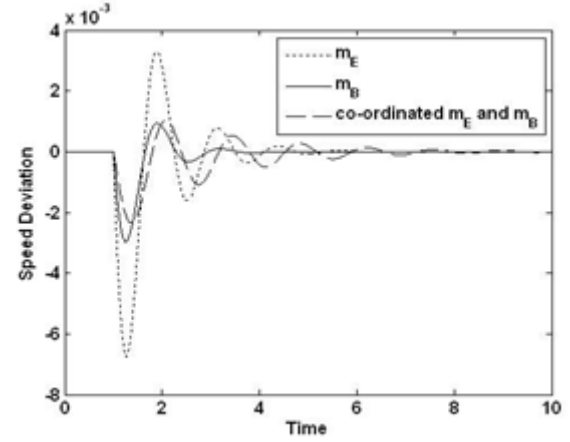


Figure 2: COC for Speed Deviation

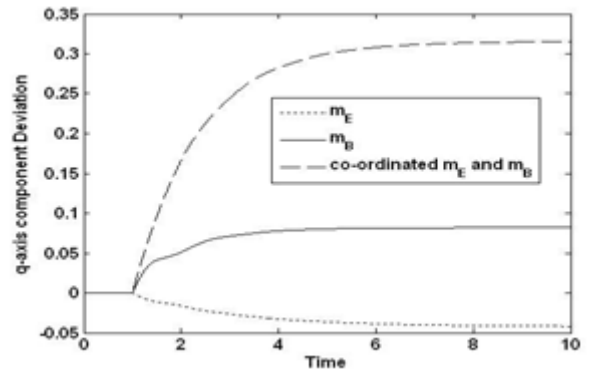


Figure 3: COC for q-axis Component Deviation

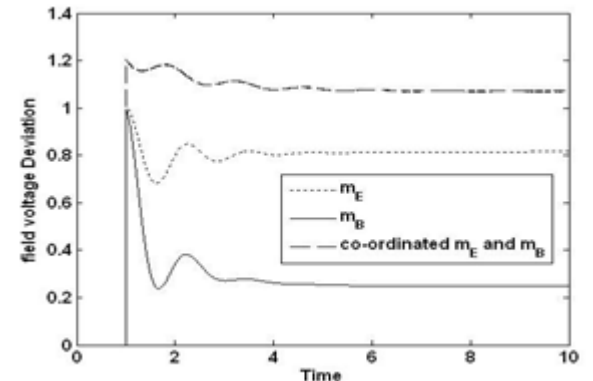


Figure 4: COC for field voltage Deviation

In view of the above optimal control analysis, investigation of Fig. 1 to 4 reveals that:

- Any of the above COC can not provide better performance for all the four state space variables with respect to peak overshoot and settling time.
- $m_E$  Provides better performance for q-axis component deviation.
- $m_B$  Provides better performance for rotor angle and speed deviations.
- The coordinated inputs and provides better performance for the field voltage deviation.

This optimal control analysis suggests that suitable switching between controllers and (corresponding to inputs and) may improve the steady state performance of all the four state space variables.

#### IV. PROPOSED OPTIMAL FEED-BACK SWITCHING CONTROL

In this section, mathematical modeling of Phillips-Heffron system with UPFC devices as a switched linear systems and the proposed switching algorithm will be explained.

##### A. Switched Linear System

Switched systems are composed of a group of subsystems guided by a switching law that governs the change among the subsystems. Use of appropriate switching in control has proved to give better performance when compared to the performance of a system without switching control. A switched-linear system model (refer Fig. 5) for the current problem is as follows:

$$\dot{x}(t) = A_{\theta(t)}x(t) + Bu \quad (2)$$

$$y(t) = Cx(t) \quad (3)$$

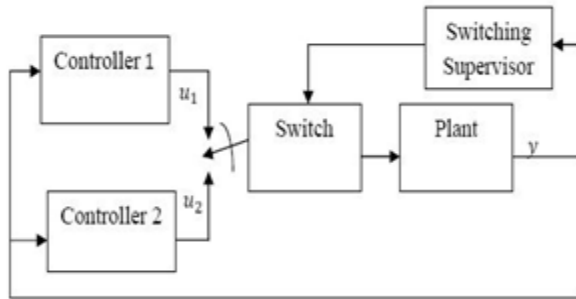


Figure 5: General implementation of switched linear systems

The switching strategy  $\theta(t)$  shown in (2) takes values 1 and 2 based on switching rule decided by the supervisor leading to closed loop  $A_1 = A - BK_1$  and  $A_2 = A - BK_2$ . The controller gain vectors can be obtained from, linear quadratic regulator theory. For the sake of completeness LQR theory is now briefly described [4]. The LQR controller generates the parameters of the gain by minimizing the error criteria in (4). Consider a linear system characterized by (1) where (A, B) is stabilizable. Then the cost index that determines the matrix K of the LQR vector is

$$J = \frac{1}{2} \int_0^{\infty} (x^T Q x + u^T R u) dt \quad (4)$$

Where Q and R are the positive-definite Hermitian or real symmetric matrix. From the above equations,

$$K = -R^{-1}B^T F \quad (5)$$

And hence the control law is,

$$u(t) = -Kx(t) = -R^{-1}B^T Px(t) \quad (6)$$

In which P must satisfy the reduced Riccati equation:

$$PA + A^T P - PBR^{-1} + B^T P + Q = 0. \quad (7)$$

The LQR function allows you to choose two parameters, R and Q, which will balance the relative importance of the input and state in the cost function that you are trying to optimize. Essentially, the LQR method allows for the control of all outputs.

Here the two controller gains  $K_1$  and  $K_2$  model the UPFC gains with respect to  $m_E$  and  $m_B$ . The controller gain is the primary controller and is the secondary controller. Thus the two closed-loop parameters will now be  $A_1 = A - BK_1$

and  $A_2 = A - BK_2$ . In order for  $K_1$  to correspond to  $m_E$  define  $K_1 = [K'_e \quad 0]^T$  and for  $K_2$  to correspond to  $m_B$  define  $K_2 = [0 \quad K'_b]^T$ . Now note that,

$$Eig(A_1) = Eig(A - BK_1) = Eig(A - BK_e) \text{ and } Eig(A_2) = Eig(A - BK_2) = Eig(A - BK_b).$$

##### B. Switching Algorithm

The switching control algorithm based on [7, 8] can be explained in the following steps:-

- Define  $K_1$  as the primary controller for  $m_E$  and  $K_2$  for  $m_B$ . where  $A_1 = A - BK_1$  asymptotically stable and

$$A_2 = A - BK_2 \text{ not necessarily stable.}$$

- Determine  $\Gamma_0$  by solving the algebraic Lyapunov Equation

$$A_1^T \Gamma_0 + \Gamma_0 A_1 = -C^T C$$

- Using,  $A_2 = A - BK_2$  define the switching matrix

$$S = -(A_2^T \Gamma_0 + \Gamma_0 A_2 + C^T C)$$

- Now, the switching rule is, use secondary controller  $K_2$  with

$$\theta(t) = \begin{cases} 2 & \text{if } \langle x, sx \rangle > 0 \\ 1 & \text{otherwise} \end{cases}$$

#### RESULTS AND CONCLUSIONS

The experimental set-up to test the proposed algorithm consists of linearised Phillips-Heffron model of SMIB installed with UPFC described by A and B (modeling and) matrices below. The primary controller and alternate controller are obtained by solving Riccati equation using R=1 and. The matrix C is a vector with zeros along with 1 in any one position depending on the state variables on which the peak overshoot and settling time is based. The proposed optimal feed-back switching rule S between two controls vector of and is also given below.

$$A = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -0.07076 & 0 & -0.0214 & 0 \\ -0.08322 & 0 & -0.4873 & 0.1982 \\ 1513 & 0 & -3516 & -100 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ -0.0474 & -0.233 \\ -0.23053 & -0.0566 \\ 4591 & 1096 \end{bmatrix}$$

$$K_1 = \begin{bmatrix} 1.166 & -48.519 & 0.668 & 0.978 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 2.127 & -149.81 & 3.859 & 0.911 \end{bmatrix}$$

$$S = \begin{bmatrix} -0.9747 & 0.9144 & 0.181 & 0.0328 \\ 0.9144 & 0.9689 & 7.833 & -0.0017 \\ 0.1811 & 7.8339 & 1.188 & 0.1286 \\ 0.0328 & -0.0017 & 0.128 & -1.0001 \end{bmatrix}$$

The dynamic response curves for the four state space variables rotor angle deviation ( $\Delta\delta$ ), speed deviation ( $\Delta\omega$ ), q-axis component deviation ( $\Delta E'_q$ ), field voltage deviation ( $\Delta E_{fd}$ ) are plotted as shown in the Fig. 6 to 9 with the legend Switch  $m_E$  and  $m_B$  for the proposed optimal feed-back switching control (OFSC) damping controllers. In order to show the effectiveness of our proposed method settling time is also tabulated for the COC and proposed OFSC.

From Fig. 1 to 4 of COC and Fig. 6 to 9 of OFSC and Table one conclude that the proposed optimal feed-back switching control provides robust performance in the steady state period and moderately better performance in the settling time in all the four state space variables simultaneously compared to system response with optimally controlled individual inputs without switching as well as optimally controlled coordinated input (MIMO model).

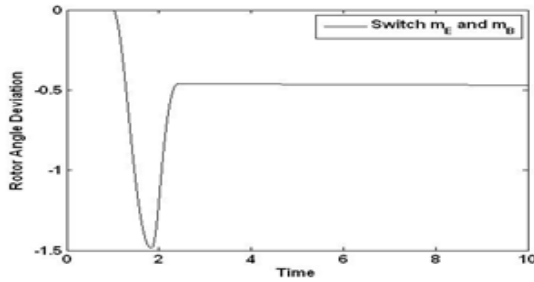


Figure 6: OFSC for the Rotor Angle Deviation

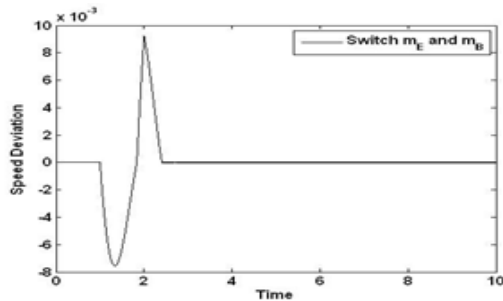


Figure 7: OFSC for Speed Deviation

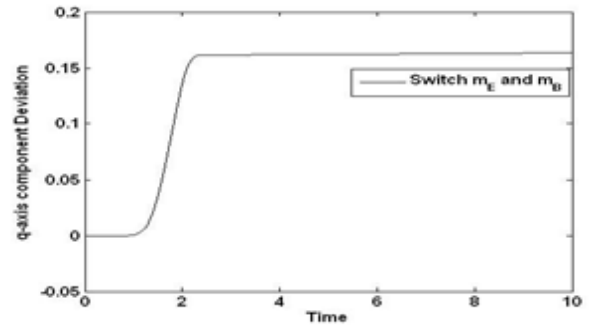


Figure 8: OFSC for q-axis component Deviation

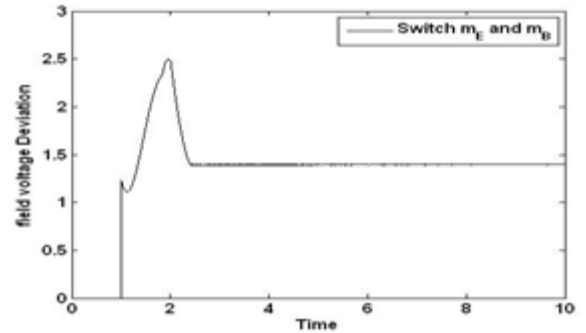


Figure 9: OFSC for field voltage Deviation

TABLE I: COMPARISON OF SETTLING TIME FOR COC AND OFSC

State variables	$m_E$	$m_B$	$m_E$ and $m_B$	Switch $m_E$ and $m_B$
$\Delta\delta$	6 s	4.3 s	7 s	2.5 s
$\Delta\omega$	6 s	4 s	7 s	2.5 s
$\Delta E'_q$	4 s	5.5 s	6 s	2.5 s
$\Delta E_{fd}$	5.5 s	5.5 s	5 s	2.5 s

## APPENDIX

Synchronous Machine:

$$H = 4.0, D = 0.0, T'_{d0} = 5.044$$

Excitation System:

$$k_A = 100, T_A = 0.01$$

$k$  Constants for the nominal operating conditions:

$$k_1 = 0.5661, k_2 = 0.1712, k_3 = 2.4583$$

$$k_4 = 0.4198, k_5 = -0.513, k_6 = 0.3516$$

$$k_{p_e} = 0.3795, k_{q_e} = 1.1628, k_{v_e} = -0.4591$$

$$k_{p_b} = 0.1864, k_{q_b} = 0.2855, k_{v_b} = -0.1096$$

$$k_{p_{\delta e}} = 1.1936, k_{q_{\delta e}} = -0.0380, k_{v_{\delta e}} = -0.0311$$

$$k_{p_{\delta b}} = 0.0529, k_{q_{\delta b}} = -0.0423, k_{v_{\delta b}} = 0.0189$$

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